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COMPARISON OF MULTISPECTRAL REMOTE-SENSING TECHNIQUES FOR MONITORING SUBSURFACE DRAIN CONDITIONS

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SUMMARY

The following multispectral remote-sensing techniques were compared to determine the most suitable method for routinely monitoring agricultural subsurface drain conditions: airborne scanning, covering the visible through thermal-infrared (IR) portions of the spectrum; color-IR photography; and natural-color photography. Color-IR photography was determined to be the best approach, from the standpoint of both cost and information content. Aerial monitoring of drain conditions for early warning of tile malfunction appears practical. With careful selection of season and rain-induced soil-moisture conditions, extensive regional surveys are possible. Certain locations, such as the Imperial Valley, Calif., are precluded from regional monitoring because of year-round crop rotations and soil stratification conditions. Here, farms with similar crops could time local coverage for bare-field and saturated-soil conditions. A final demonstration of the applicability of subsurface drain monitoring using aerial photography over a variety of soil types is now appropriate. A joint NASA, USDA, University, and Farm Cooperative Program may be a viable approach.

INTRODUCTION

Subsurface drain lines are installed on farms to alleviate waterlogging problems and, in the arid western states, to create and maintain a favorable soil-salt balance (ref. 1). For example, approximately 80% of the 500,000 irrigated areas in the Imperial Valley, Calif., are drained by subsurface drain lines. Of this acreage, approximately 65-70% is affected by clogging or sealing caused by deposits of iron or manganese compounds, soil sedimentation within the pipes (silt plugs), or by the accumulation of roots (root plugs). This problem is not limited to the Imperial Valley. Within the past 5 to 10 yr, farmers in the San Joaquin Valley, Calif., have begun to equip their farms with subsurface drains (ref. 2). Farmers in the Columbia River Basin in eastern Washington are installing subsurface drains to alleviate waterlogging problems that are developing there; clogging has developed and has become severe in some locations. Drain malfunctions also occur in Indiana, Ohio, Michigan, Oregon, Florida, parts of Canada and, to a lesser extent, in other states in the U.S.A. Drain malfunctions have been observed in the United States, England, Holland, Poland, Sweden, and Russia. In general, drain malfunctions occur wherever subsurface drains are used (ref. 3).

This study compares various multispectral remote-sensing techniques for monitoring subsurface drain conditions, and determines requirements and limitations for

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their successful and economical application. All data used for this comparison were obtained from the Imperial Valley, near Brawley, Calif.

THE ECONOMIC IMPACT

Drainage Failure

Inefficient drainage systems lower crop yields. It is very difficult to assess quantitatively how much of the reduced yields result from defective drainage systems because so many factors impinge on production yields, such as weather changes, crop rotations, pests, and different fertilizers. However, if the drainage system is ignored altogether and salt deposits increase, the result could be the complete loss of a plot of land for agricultural production. Two approaches used to control clogged drain-line problems are preventive maintenance and land reclamation. Compared with drain-maintenance costs, land-reclamation costs are high because of the extra water required for leaching and the costs of labor, equipment, and new drain lines.

Table 1 shows 1982 costs for installing drain lines in the Imperial Valley. The cost ranges from \$2.13/m to \$6.95/m for the more commonly used pipe diameters. In the Imperial Valley, 0.4- and 0.8-km (0.25- and 0.5-mile) lateral runs are common. A lateral 10 cm (4 in.) diameter would cost \$1162 to \$2323 for each length. The number of laterals or "runs" required depends upon the soil texture. Many 32-ha (80-acre) fields in the Imperial Valley have four to eight 0.8-km-long laterals. This represents a variation in cost of \$9292 to \$18,584 or \$290/ha to \$580/ha (\$116/acre to \$232/acre). These figures do not include the cost of the baseline (collector line).

TABLE 1.- COSTS OF SUBSURFACE DRAIN INSTALLATION IN THE IMPERIAL VALLEY IN SEPTEMBER 1982

Pipe diameter[a]		Installation equipment		Installation cost	
in.	cm	Plow	Trencher	Cost/ft	Cost/m
2[b]	5[b]	X		\$0.45	\$1.48
3	8	X		.65	2.13
3	8		X	.78	2.56
4	10		X	.88	2.89
6	15		X	1.75	5.74
8	20		X	2.12	6.95
12	30		X	6.00	19.68

[a]Currently, plastic pipes are used entirely for all drain systems.
[b]New pipe size introduced into the market in September 1982 in the Imperial Valley.

Preventive maintenance is practiced by periodically cleaning drain lines using high-pressure water hoses (ref. 4). Even this approach is relatively expensive, costing \$0.49/m of lateral length. Thus, the technology to clean and reclaim clogged or sealed drains exists. However, at present the farmer does not have a means of detecting the problem until it becomes severe enough to reduce his crop yields.

Monitoring for Early Signs of Failure

If a drain malfunction could be detected at an early stage, corrective action could be initiated at a relatively low cost. An added benefit would be knowing where and when action was required. This would be a considerable saving over any routine preventive maintenance program for which the cost of high-pressure water cleaning can be about $42,000 for one section of land with drain lines at 30.5-m (100-ft) intervals. Contracted routine "ground truthing" would be costly. Normally, the farmer does not have the facility or the time to monitor the out-flow from each individual drain line. Thus, the need for a cost-effective remote monitoring approach exists. Airborne observations appear to offer the best solution. Previous work has shown that drains in highly saturated soils are easily observed using aerial photography, as can be seen in figure 1. This photograph was taken over agricultural land located near Brawley, Calif. by a U-2 aircraft on October 31, 1979. Drying patterns are visible in many of the fields.

REMOTE-SENSING TECHNIQUES

Water Movement and Drying Patterns

When drains are functioning properly, soils exhibit a characteristic drying pattern over a period of several days following an irrigation. For a fully saturated bare field, strips of dry soil first appear directly over the drain positions, and gradually widen each day until the entire field surface appears equally dry. The physics of water movement in saturated soils is complex and is controlled by numerous soil parameters and energy-balance considerations. Serious theoretical and experimental studies on saturated flow in homogeneous soils by Baver (ref. 5) and Buckman et al. (ref. 6) showed that the water movement through soils toward a drain is complex. Not only does the flow move downward and laterally to a drain, but under some conditions the flow also moves laterally and upward, entering a drain from beneath. The presence of an inhomogeneous soil layer, i.e., a soil of differing hydraulic conductivity, further complicates water movement and thus the subsequent drying patterns. These studies were conducted under careful laboratory conditions; to repeat these observations under field conditions would be a monumental undertaking beyond the scope of this study.

The physical process dominating the saturated moisture condition of an agricultural field is the water movement from an irrigated field surface to the water table below. Surface-drying rates and patterns are influenced by whether drains are working or malfunctioning. When a drain becomes clogged, the water table in its vicinity rises, limiting the downward movement of water from the surface. Consequently, the surface remains wet. When a drain is working properly, gradually widening dry areas occur, as mentioned earlier. Thus, it is not the actual physical process that is monitored remotely, but rather the manifestation of soil-water movement, as exhibited by the drying patterns. Anomalous pattern behavior could be indicative of drain malfunctions.

Drying patterns are manifested in various ways, depending on whether the soil is bare or crop covered. For bare soils, the surface of a wet area will appear much darker than that of a dry area. The reflectance of wet soil is about one-half that of dry soil. The midday temperature difference between wet and dry soil is also large. This difference can easily be 10°C.

For crop-covered conditions, the anomalous drying pattern may manifest itself in the vigor of crop growth. Over a long period, high water tables have deleterious effects on plant vigor, and variations in canopy vigor among homogeneous types of

of crops are easily detected by remote-sensing techniques. The temperatures of crop-covered fields are influenced by the soil moisture. Plant stomata open and close to provide evaporation. In general, the temperatures of a healthy plant will be close to that of the ambient air. It is known that the temperature of a plant suffering from lack of water will rise above ambient temperature by as much as 10°C. On the other hand, a crop under too much water stress will also exhibit a temperature anomaly. Thus, thermal imagery was considered to be potentially useful for detecting problems in crop-covered fields.

Technique and Technology Evaluation

Before evaluating airborne remote-sensing techniques for monitoring agricultural drain tile conditions, we had to determine (1) the characteristics of surface drying patterns over clogged and unclogged drains, (2) the effect on observations of various plant growth stages and soil textures, (3) the optimum time of day and flight altitude for data-taking, (4) whether color-IR photography would be superior to natural color photography, and (5) whether multispectral-scanner data (i.e., thermal-IR, near-IR, and visible-channel measurements) would be required to fully diagnose the conditions of a drainage system.

Three spectral bands were selected for special attention: the 10.5- to 12.5-μm thermal- (or emitted-) IR waveband, the 800- to 890-nm near-IR (Ch.9) waveband, and the 600- to 650-nm red (Ch. 6) waveband. Near-IR radiation is highly reflected by green vegetation and was chosen to emphasize canopy vigor differences. The reflected radiation in this waveband provides a contrast companion to the red-waveband radiation, which is highly reflected by bare soil. The ratio, near-IR/red (Ch. 9/Ch. 6), known as the "vegetative index," is an extensively used analytical tool in agricultural research.

Since this program was constrained by limited resources, a two-phase flight program was designed to combine all existing technologies, with "targets of opportunity" appearing along predetermined flight lines. Figure 2 is a mosaic showing the region of the Imperial Valley near the Salton Sea where the flight program was conducted. This photograph was taken on December 2, 1981, by a U-2 aircraft flying at an altitude of 19.8 km (65,000 ft).

An initial series of flights (November 1980) concentrated on a coarse-textured-soil, vegetable-growing region on the west side of the valley. The flight lines are shown as black and white lines in figure 2. Data were collected using a Daedalus 11-channel airborne scanner system and an RC-10 22.9-cm (9-in.) format, 15.2-cm (6-in.) focal-length-lens aerial camera using color-IR Type 2443 film. These flights were repeated four times at 4-day intervals. The results answered most of the questions posed above, and led to the design of a series of five flights (June 1981) over areas of the Imperial Valley with fine-textured soils. The choice of particular flight lines was based on knowledge of the local cropping practices. Thus, flight lines were set to maximize the probability that freshly irrigated fields of various soil textures and varying stages of growth would be observed.

AERIAL OBSERVATIONS

November 1980 Flight Series

Flights were made on November 13, 18, 21, and 25 at altitudes of 3050 m, 1520 m, and 610 m along the black and white lines shown in figure 2. The first data run started at 0930 Pacific Standard Time; about 45 min were required to complete the three altitudes. The first afternoon data run started at 1300 Pacific Standard Time.

Figures 3a and 3b are enlarged sections of single frames selected from the 3050-m color-IR photography from two of the flight dates. Figure 3a shows two freshly irrigated bare-soil fields on November 13. Drying in the lower center field has progressed to a stage where the field drain pattern is clearly visible. The drain positions are indicated by the narrow, vertical, light-colored strips. Soil directly over a functioning drain dries first.

Figure 3b shows the appearance of the two fields on November 21. The lower center field has retained its symmetrical appearance with the widths of the dry areas over the drains having increased equally with time. This is believed to be an excellent example of a well-functioning drainage system.

The upper right-hand field presents a far different picture. Two drains located on the left side of the field appear to be functioning as evidenced by the increasing vertical dry-soil regions. On the right side of the field, very little drying has occurred during the 8-day interval between the two observations. Obviously, these drains are running at a very slow rate. This field is an example of one observed failure mode: partial degradation of the drainage system resulting in unacceptable drying times. This may occur in part of a field or over the entire field.

Figures 4a and 4b demonstrate the appearance of a field with catastrophic drainage failure. Figure 4a, taken on November 21, shows a freshly irrigated field (bordered in black) of fairly normal appearance. Figure 4b, taken on November 25, shows a mottled drying pattern even though the drain positions are clearly marked by the horizontal strips. Examination of photographs taken for dry-soil conditions (November 13 and 18) showed the soil to be homogeneous. Thus, the uneven drying pattern was the result of a malfunctioning drain tile system. This conclusion was confirmed when the entire tile system was later replaced.

June 1981 Flight Series

Flights were made on June 1, 6, 11, 16, and 21, at altitudes of 3050 m starting at about 1100 Pacific Standard Time and 1520 m starting at about 1230 Pacific Standard Time along the solid black lines shown in Figure 2.

Coarse-textured soil- Coarse-textured, sandy-soil fields were located mainly along the western half of the valley (figure 2). This region incorporates a large population of vegetable-growing fields.

Photographic evidence. Data on drying patterns observed on coarse, sandy fields were similar to the November 1980 flight series. Figure 5a shows three small adjoining fields (bordered in black), in an early stage of their drying cycle. If this single observation, made on June 21, had been the only one available for analysis, a drainage failure would have been concluded from the uneven appearance of the drying pattern. Examination of the three fields during dry-soil conditions (Figure 5b, June 16) shows the field soils to be very inhomogeneous. A close comparison between figures 5a and 5b shows that most of the uneven patterns of wet soil (fig. 5a) directly match the areas of soil with reduced reflectivity, and thus a drainage failure cannot be concluded. This result has two important implications: interactive data sets showing fields under drying conditions, and also in a dry-soil stage, are required for accurate drainage analysis; and within-field inhomogeneity complicates analysis, and may greatly reduce analysis accuracy.

Multispectral observations. Multispectral scanner measurements were made during the November 1980 flight series and on the June 21 flight. Thermal-IR and color-IR photography were obtained for all flights.

Figure 6 is a black and white reproduction of a pseudo-colored, computer-generated image (ref. 7) of near-IR (Ch. 9) data gathered on June 21 in a region on the west side of the Valley at the start of the south-to-north flight line (solid

black line in fig. 2). Figure 7 is a computer-generated image of thermal-IR data from the same region, gathered on June 16. No comparable thermal image for June 21 was available because of a malfunction in the thermal detector on that date. The computer-generated images for the red channel (Ch. 6), and the near-IR/red (Ch. 9/Ch. 6) ratio look essentially identical to figures 6 and 7 except for different color patterns and different color-level values. Extensive examination of all fields observed along the flight lines showed the following.

1. Nearly all drain patterns detected by measurements of thermal-IR, near-IR, red, or near-IR/red ratios were also observable with color-IR photography.

2. A few drain patterns under crop cover were detected by the thermal-IR data only, but no pattern changes were noted over the observation period.

3. Drying patterns in bare-soil fields were visible in the thermal-IR data for a longer period into drying than with color-IR photography.

4. Near-IR, red, and near-IR/red ratio measurements were not adequate to determine drying patterns under crop canopies, and for bare-soil fields, these techniques were no improvement over color-IR photography.

5. No definitive conclusion on drain conditions could be made by multispectral observation of vegetative vigor alone.

Fine-textured soils- Most of the fine-textured-soil fields are located across the northern end and on the eastern side of the Imperial Valley (fig. 2). Only a single drying pattern (fig. 8) was detected during the flight series. These two fields were cultivated the following day, terminating any further observation.

December 1981 Flight

A U-2 aircraft flight was made employing dual RC-10 cameras with 305-mm (12-in.) focal-length lenses to compare color-IR and natural-color imagery. High-definition aerochrome IR, Type SO-127, spectral-band 510- to 900-nm film was used in one camera, and aerial color, Type SO-242, spectral-band 400- to 700-nm film was used in the other. Frames from the Type SO-127 film were used to construct figure 2. Essentially, there was no difference between color-IR and natural-color photography for distinguishing in-field features. Identification of crop cover, particularly sparse crop cover, was more easily accomplished with color-IR photography.

STATISTICS

Coarse-Textured Soil

For both the November 1980 and June 1981 flight series, about 30% of all fields observed along the flight lines were in a bare-soil (no-crop) state. During the two observation periods, 25% of the bare fields had either been recently irrigated or were irrigated during the period of observation. Of these, about one-eighth of the fields exhibited drying patterns sufficiently detailed to support conclusions about the condition of their drainage systems. Thus conclusions could be inferred from about 1% of all the fields observed.

Fine-Textured Soil

Only a single observation of a drain drying pattern was made and therefore no statistics were compiled.

RESULTS AND DISCUSSION

Coarse-Textured Soil

For the various remote-sensing techniques evaluated, results can be summarized as follows.

First, on an operational basis, drain monitoring by color-IR photography is equal to thermal-IR, near-IR, red, near-IR/red ratios, and natural color photographic methods. For cost effectiveness, it is superior to any of the multispectral techniques.

Second, observations of a drying pattern over a complete irrigation cycle are mandatory, and observations over more than a single irrigation-drying cycle increase the accuracy of analysis.

Third, flight altitudes may be determined solely by the area of interest, and there is no preferable time of day for making observations. In the November flight series, no altitude differences were found. Ground resolution for both photographic and scanner data were adequate for all flight levels. Also, photographic, thermal, and spectral data were similar for morning and afternoon flights. Note, however, that cloud shadows on a target field negate analysis.

Any crop growth, either partial or full canopy, obscures the soil drying patterns so that no direct analysis of drain-functioning is possible. When drying patterns were visible through crop cover, the patterns appeared constant over all observation dates. Thermal-IR scanner data enhanced the drying patterns but, like the color-IR photography, detected no pattern size change over the observation period.

Observation of bare-field drying patterns was possible for a longer period of time into the drying cycle using thermal-IR instrumentation than was possible using color-IR photography. Figure 9 shows the change in width, over time, of the dry soil strips of the two fields depicted in figures 3a and 3b measured from thermal-IR images. Here, field 3 is the lower (healthy) field in figure 3a and field 2 is the left (functioning) side of the upper field shown in figure 3b. The research potential for using thermal-IR techniques to study nonsaturated moisture movement under field conditions is thus illustrated. In this single example, the drying area in a coarse sandy field was found not to be linear, but appeared to double in size with time.

Fine-Textured Soil

The lack of information gathered for fine-textured-soil areas appears to be due to soil stratification and inadequate soil-moisture profiles rather than a failure of the observation methods. The fine-textured-soil areas of this region are highly stratified, causing applied surface water to move in a lateral, rather than downward, direction. Thus, for the normal amount of irrigation water applied to these fields, the moisture profile required to produce visible drain patterns was not obtained.

Figures 10a and 10b support the conclusion that drying patterns can be observed for fine-textured soils. These photographs show an area in the lower Rio Grande Valley near Pharr, Texas, following Hurricane Beulah in September 1967. Figure 10a shows the situation (September 30, 1967) 5 days following the antecedent rainfall

estimated to have been 44 cm. The soil of the area shown is Raymondville Clay Loam (over 30% clay), with clay-loam texture typically extending to a depth of about 1.1 m and clay below that.

Figure 10b shows the situation on December 4, 1967, 70 days following the hurricane rainfall. Eight centimeters of rain fell in the period after the hurricane, from 21 to 28 days before the figure 10b photograph was taken. The dry-soil surface over functioning subsurface drains can be seen. The limited width of drying over drains after 21 rainless days can be attributed to the fine soil texture and the low potential evaporation of 4 mm or less per day during this period of the year (Nixon, Paul R., private communication, 1982). The low potential evapotranspiration may have aided in the sustained visibility of subsurface drainage patterns. This needs further investigation as a desired condition for observing patterns in fine-textured soils.

Unfortunately, photographic coverage of the area and local groundwater measurements between September 30 and December 4 are not available, so it is not known what residual influences there may have been on December 4 from the hurricane 70 days earlier. Retarded drainage caused by regional influences could have resulted in wetter conditions than normal when the 8-cm rain fell in November, making that amount of rainfall equivalent to a greater rainfall (or irrigation) than normal. The important point illustrated by figure 10b is that patterns of functioning subsurface drains can, with a proper soil-moisture profile, be observed in fine-textured soil.

CONCLUSIONS

Regional monitoring of drainage conditions is possible with careful choice of time and weather conditions. The optimum would be completely bare fields saturated with moisture. Such conditions often exist in the east, midwest, and western states prior to planting and just after heavy spring rains. Large regions can be easily documented by high-altitude photography such as that provided by the U-2 in figure 1.

Certain locations, such as the farming area near Brawley, Calif., used for this study, present a unique challenge for monitoring subsurface drainage. Besides the particular irrigation practices that do not normally result in the required moisture profiles for fine-textured soils, crop rotation in the Imperial Valley results in many of the fields being planted over the entire year. Thus, at no time are all the fields bare.

The best approach here would be for growers of similar crops to contract with a local aerial-survey firm to over-fly their area when the fields are bare and new irrigation has been applied. Likewise, fine-textured-soil fields could be timed for monitoring when bare and after sufficient irrigation has been applied to produce moisture profiles required to reveal subsurface drainage patterns.

A final demonstration of the applicability of subsurface drain monitoring using color-IR aerial photography in diverse-soil-type regions may now be appropriate. Special test fields selected by a consortium of NASA/USDA regional offices and local universities could be "ground-truthed" while local aerial survey firms would produce appropriate photographic imagery. Interested regional farm cooperatives could participate and provide valuable "feed-back" on whether the data was producing information which could be utilized by their members to help solve unique local problems.

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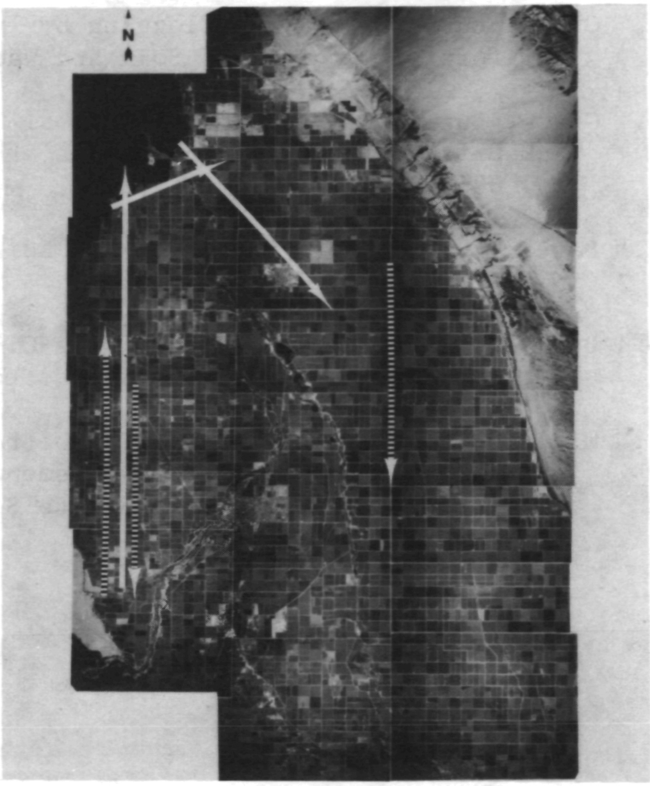
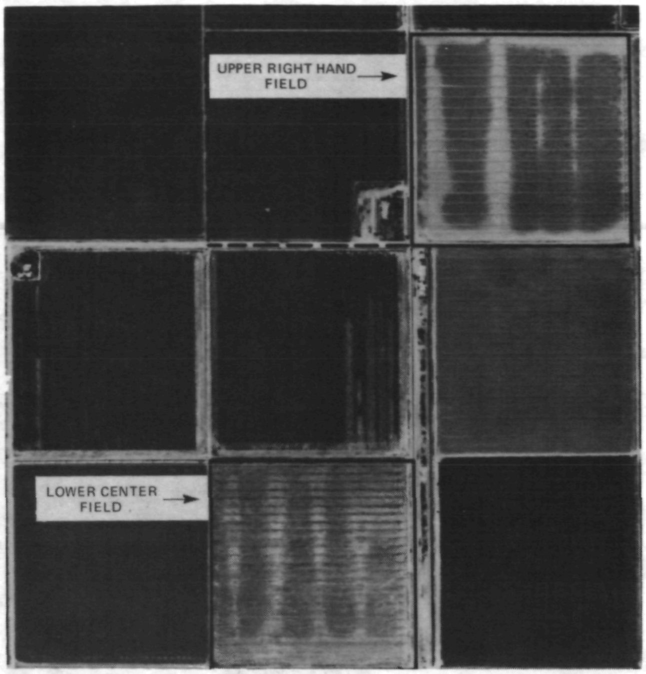


Figure 1.- U-2 photograph of area of Imperial Valley showing visible subsurface drainage patterns.

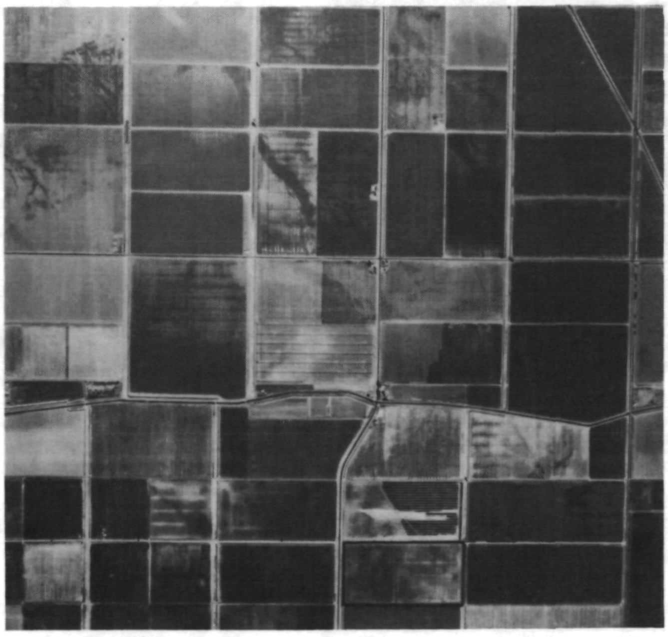
Figure 2.- Mosaic of Imperial Valley showing November 1980 and June 1981 flight lines.

(a) Freshly irrigated fields.



(b) Symmetrical and nonsymmetrical drying patterns.

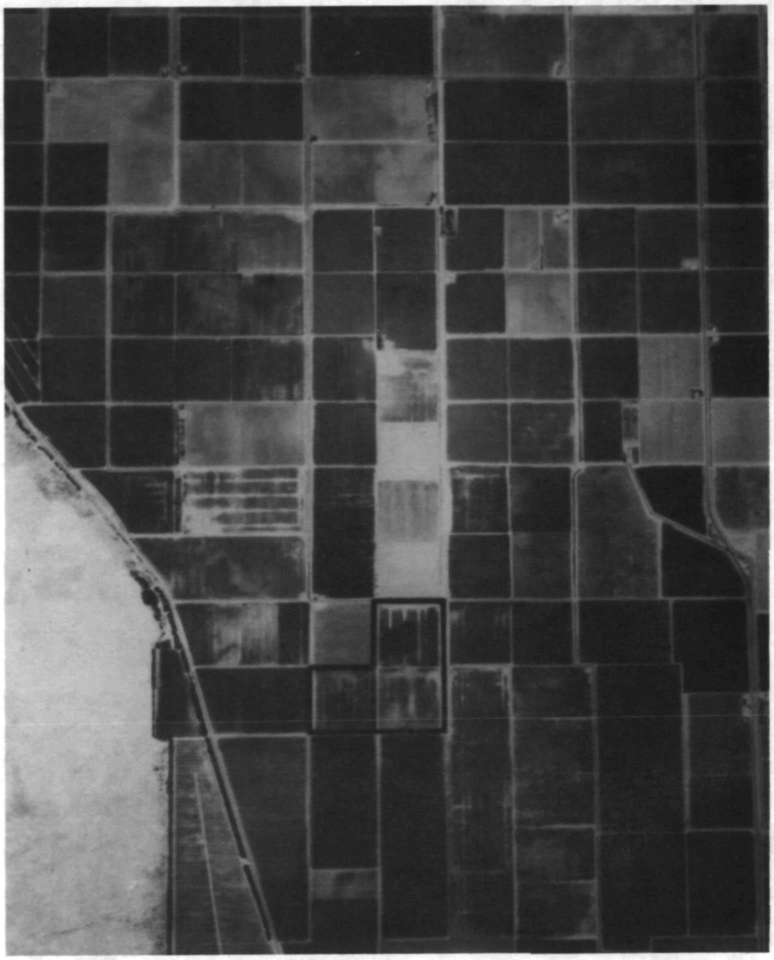
Figure 3.- Photograph of two bare fields.



(a) Wet field.

(b) Mottled appearance of drying pattern 4 days later.

Figure 4.- Photograph of bare field with catastrophic drainage failure.



(a) Wet fields, showing uneven drying patterns and areas of wetness.

Figure 5.- Three adjoining bare fields.

(b) Dry fields, showing areas of nonhomogeneous soil types.

Figure 5.- Concluded.

Figure 6.- Computer-generated image of near-IR (800- to 890-nm) data.

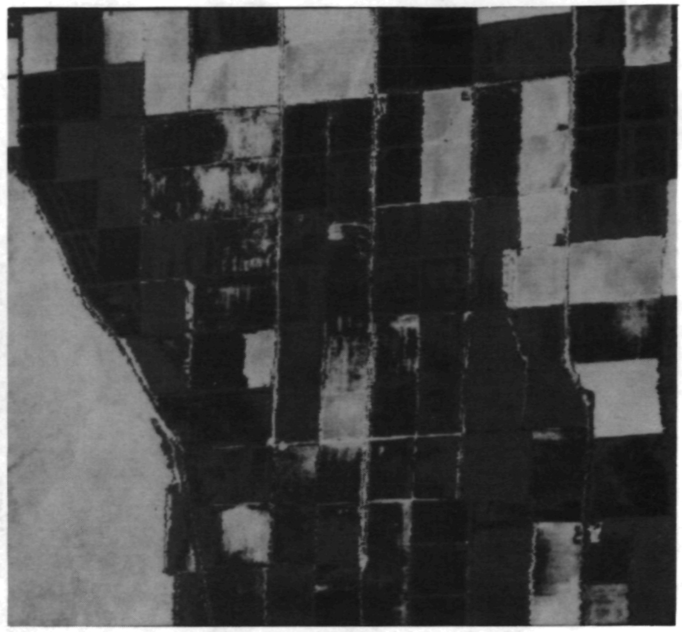


Figure 7.- Computer-generated image of thermal-IR (10.5- to 12.5-μm) data.

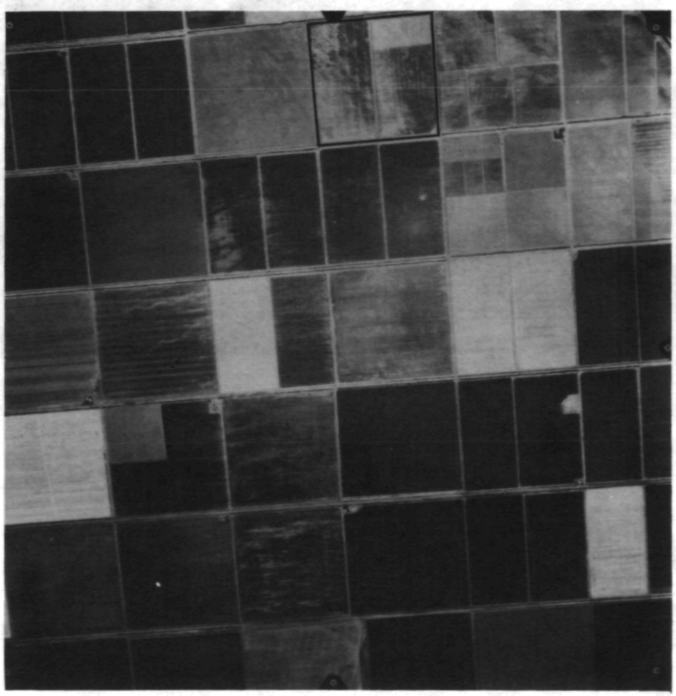


Figure 8.- Photograph of subsurface-drain drying patterns in fine-textured soils.

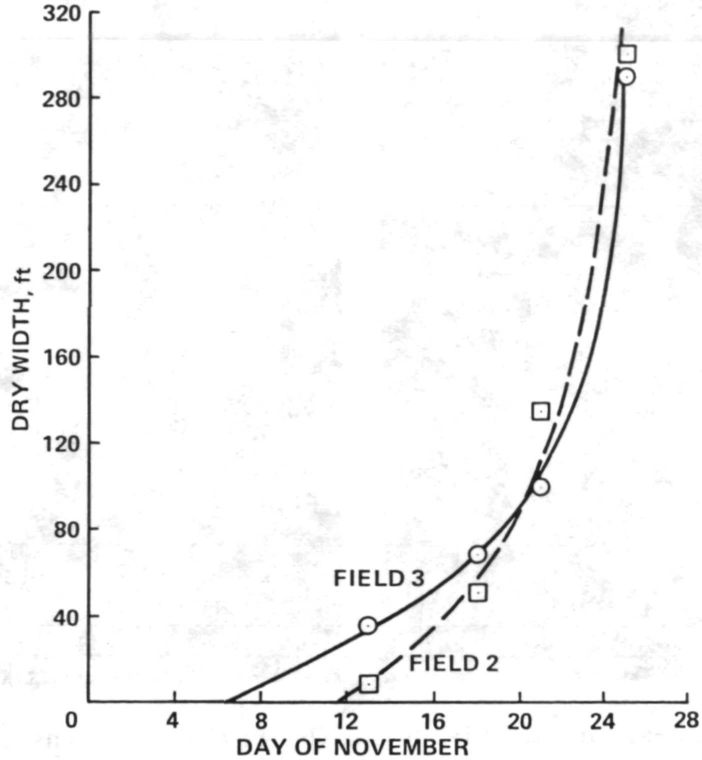
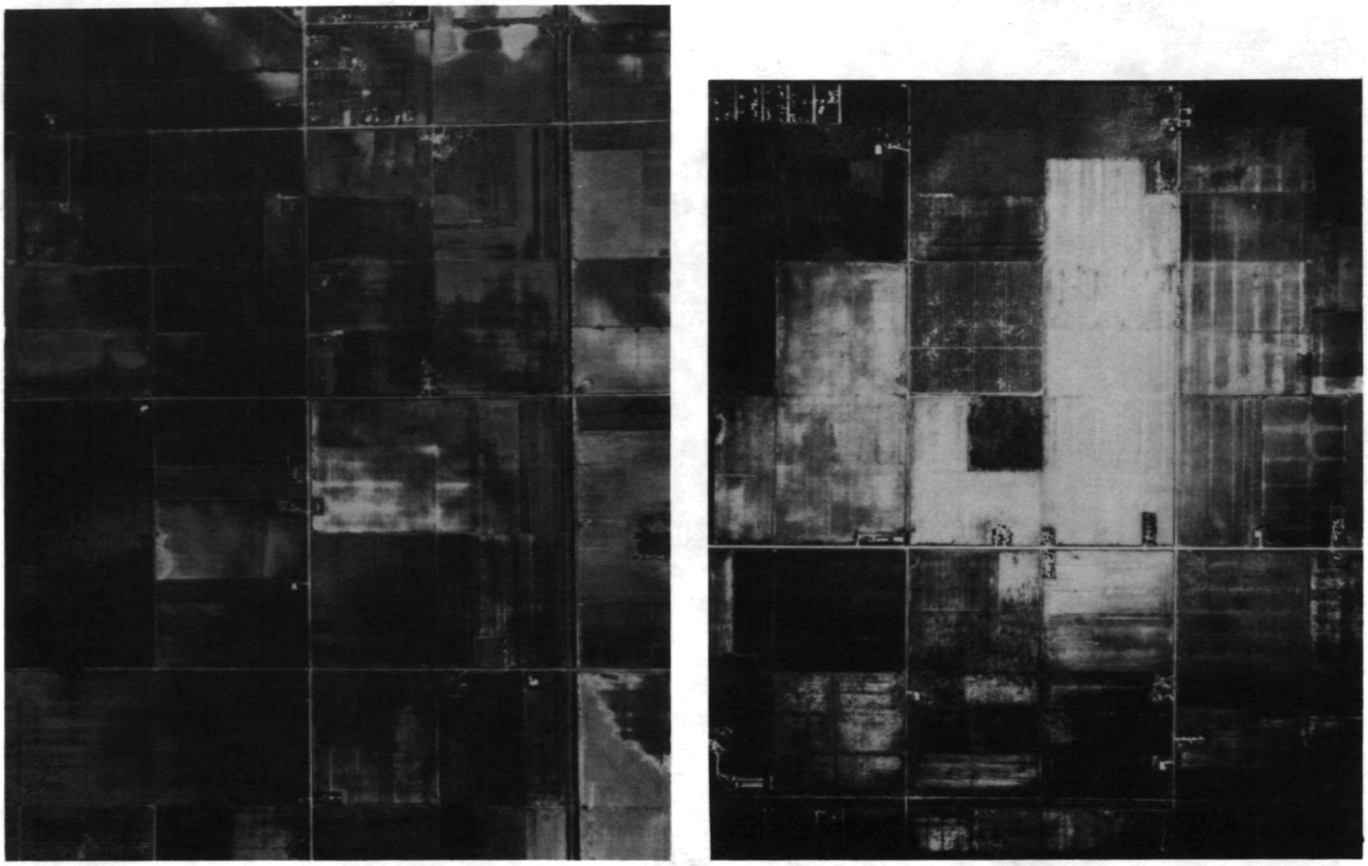


Figure 9.- Width vs time of drying patterns over functioning drains in two coarse-textured-soil fields.



(a) Rainwater hurricane-saturated fields. (b) Drying patterns in the same fields 70 days later.

Figure 10.- Photograph of fine-textured-soil fields.

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15. Supplementary Notes

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16. Abstract

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